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Coalesced effect of cavitation and silt erosion in hydro turbines—A review

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ABSTRACT

Cavitation is a phenomenon which manifests itself in the pitting of the metallic surfaces of turbine parts because of the formation of cavities. However, silt erosion is caused by the dynamic action of silt flowing along with water, impacting against a solid surface. The erosion and abrasive wear not only reduce the efficiency and the life of the turbine but also cause problems in operation and maintenance, which ultimately lead to economic losses. Researchers have studied that the cavitation in silt flow is more serious than in pure water. However, the coalesced effect of silt erosion and cavitation is found to be more pronounced than their individual effects.

In the present paper the studies in this field carried out by various investigators are discussed and presented. Parameters related to the combined effect of cavitation and silt erosion which are responsible for efficiency loss due to erosion as investigated by researchers have also been discussed.

Contents

1. Introduction

The global installed hydropower capacity excluding pumped storage hydropower was estimated to be between 926 GW and 956 GW in 2009/2010 [1]. Presently in India the total installed capacity including all the resources is 126,089 MW and the share of hydro energy is 26% [2]. A hydropower plant consists of civil, mechanical and electrical components. The hydraulic turbine being the heart of any hydro plant transforms the potential energy of water into mechanical energy in the form of rotation of a shaft [3]. In the case of medium and low head hydropower plants, turbine cost contributes around 15%–35% of the overall cost of a hydropower plant [4]. The factors affecting efficiency of hydro turbines are related to leaking of the water without any work being done, secondary flow within the flow passage or friction losses due to roughness of the surface. However, the main reason for efficiency and performance loss over a period of turbine operation is erosive power of turbine components due to the main parameters of silt, cavitation and corrosion. *The present paper discusses the studies carried out by various investigators in order to determine the effect of silt, cavitation and coalescence effect on hydraulic machines and to indentify gaps for future studies.*

2. Investigation on silt erosion

The presence of silt in water is very common in hilly regions and most run-of-river plants. The hydro turbines experience severe problems of silt erosion. In general erosion damage is considered

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as the gradual removal of material caused by repeated deformation and cutting actions. Silt erosion is designated as abrasive wear. This type of wear breaks down the oxide layer on the flow guiding surfaces and partly makes the surfaces uneven, disturbs the flow and results in friction losses. Erosive wear of the turbine blades is a complex phenomenon that depends on (i) the eroding particles, their size, shape, hardness and concentration; (ii) substrates, chemistry, elastic properties, surface hardness and surface morphology; and (iii) operating conditions, velocity and impingement angle [5,6]. The hydro-abrasive wear was commonly quantified by means of wear rate, W, defined by loss of mass per unit time and expressed as [7]

$$W = f(\text{properties of eroding particles; properties of base material; operating conditions}).$$

Padhy and Saini [7] presented a review on silt erosion in hydro turbines. They discussed various aspects related to silt erosion in hydro turbines, different causes for the declining efficiency of hydro turbines and suitable remedial measures suggested by various investigators. It was shown that silt erosion problem is a major concern in the case of small hydropower plants, as most of these plants are run-of-river schemes and are situated in steep hilly terrains.

Padhy and Saini [8] investigated the effect of size and concentration of silt particles on erosion of Pelton turbine buckets. They studied the effect of the parameters on erosion in actual conditions on a small scale Pelton turbine. Using the experimental data collected for different parameters, correlations have been developed for wear rate of Pelton turbine buckets as a function of critical parameters, i.e., silt size (S *in meter*), concentration of silt particles(C *in ppm*), jet velocity (V in m/s) and operating hours of the turbine (t *in hour*). The final form of the correlation for normalized erosive wear rate (W in g/g/m^3 s) obtained excluding pumped storage hydropower capacity is as follows:

$$W = 4.02 \times 10^{-12}(S^{0.0567})(C^{1.2267})(V^{3.79})(t) \tag{1}$$

Neopane et al. [9] investigated the effect of particle shape and size on hydraulic turbines. A test rig was designed to investigate different shapes and sizes (1–10 mm) of silt particles. Different shapes and sizes of particles were tested with the same operating conditions and it was found that triangular shaped particles were more likely to hit the suction side of the guide vane cascade.

Neopane et al. [10] conducted a *numerical study* to predict the particle shape factor effect on sediment erosion in Francis turbine blades. The simulation was based on the Lagrangian particle tracking multiphase model available in ANSYS-CFX. The modeling involved the separate calculation of each phase with source terms generated to account for the effect of the particles. *The study found that* erosion on turbine blades strongly depends on the shape of the particle.

Kurosawa et al. [11] presented a method for the prediction of erosion characteristic of a hydro turbine runner under different conditions. The sand particle behavior was predicted by solving two phases flow equations based on a Lagrangian model and the whole flow passage models. The mass eroded was calculated by applying the polynomial experimental function, considering particle impact velocity and impact angle. Further, the erosion mass of the prototype turbine runner was *calculated* by conducting the sand erosion analysis under different operating conditions. The analytical results were integrated according to the weight-average treatment. *The analytical results were verified with the inspection results for the target runner to show that the prediction accuracy for the eroded wear part is in the same order*. Based on the investigations the principal causes of erosion in a Francis turbine runner were predicted.

3. Investigation on cavitation effect

Cavitation is a term used to describe a process, which includes nucleation, growth and implosion of vapor or gas filled cavities. These cavities are formed in a liquid when the static pressure of the liquid is reduced below the vapor pressure of the liquid at current temperature. When cavities are carried to a higher-pressure region they implode violently and very high pressures can occur. Prof. D. Thoma suggested a dimensionless number, called Thoma's cavitation factor σ, which can be used for determining the region where cavitation takes place in reaction turbines:

$$\sigma = \frac{(H_a - H_v - H_s)}{H} \tag{2}$$

where H_a is the atmospheric pressure head in m of water, H_v is the vapor pressure in m of water corresponding to the water temperature, H_s is the suction pressure at the outlet of reaction turbine in m of water or height of the turbine runner above the tail water surface, and H is the net head on the turbine in m of water [12,13]. The value of Thoma's cavitation factor (σ) for a particular type of turbine is calculated from Eq. (2). This value of Thoma's cavitation factor (σ) is compared with critical cavitation factor (σ_c) for which the turbine is designed. If the value of σ is greater than σ_c cavitation will not occur in that turbine.

For safe operation (cavitation-free) of a turbine, it is evident that

$$\sigma > \sigma_c \tag{3}$$

The following empirical relationships are used for obtaining the value of σ_c for different turbines [14]. For a Francis turbine

$$\sigma_c = 0.625(N_s/380.78)\hat{}\,2 \tag{4}$$

For a propeller turbine

$$\sigma_c = 0.28 + ((1/75)(N_s/380.78)\hat{}\,3)) \tag{5}$$

where N_s is the specific speed of the turbine. *It is expressed by* $(NP\hat{}\,0.5)/(H\hat{}\,1.25)$, *the value of speed* ($N$) *in rpm*, *power* ($P$) *in* kW *and head* ($H$) *in meter*. For a Kaplan turbine, σ_c value obtained by Eq. (5) should be increased by 10%.

The parameters σ must be above a certain value to avoid cavitation problems. It is difficult to guarantee the complete elimination of cavitation; however, cavitation can be brought within acceptable limits.

Kumar and Saini [15] presented a review on cavitation in hydro turbines which presents various aspects related to cavitation in hydro turbines. Causes for the performance and efficiency losses of the hydro turbines and suitable remedial measures suggested by various investigators have been discussed in the paper.

Cojocaru et al. [16] numerically investigated the flow behavior in a Kaplan turbine runner blade having an anti-cavitation lip with a modified cross section. It was predicted that the flow behavior for two types of geometry of Kaplan runner blade; a first lip is of original dimensions and the second lip of modified smooth edges at the extremities. The pressure coefficient at the extremities of the lip was found to have a significant variation of about 0.2 to −0.6 and the cavitation caverns appear to be at the extremities of the lip.

Shi et al. [17] performed an experiment on cavitation in a Kaplan turbine. Experimentation was carried out according to IEC 60139 in three stages: a model test, prototype tests for different operating conditions and a comparison of test results with the findings using the prototype turbine with the repaired blade. The tendency of cavitation intensity along with cavitation coefficients was analyzed and the cavitation sound was identified via model tests. The results were monitored through on-line monitoring systems on 3F, 10F, 14F, 19F and 21F turbines in the Gezhouba

hydropower plant. Cavitation vibro-acoustic signal and ultrasonic signals were measured individually with 4 accelerometer and 4 acoustic emission (AE) sensors. The cavitation intensities for different values of head and load were traced out from the test results in different operating stages of the Kaplan turbine. The cavitation erosion level was estimated according to the cavitation intensity at a fixed operating state such as rated power and designed water head.

Franc et al. [18] studied cavitation erosion pitting. The incubation period of cavitation was investigated via pitting tests conducted on three different materials i.e. Aluminum alloy, a Nickel Aluminum Bronze alloy and a Duplex Stainless Steel, in a cavitation tunnel. The velocity ranges of 45–90 m/s *were* varied at a constant cavitation number. It was suggested that other parameters such as the strain rate might play a significant role and should be included in the analysis. The effect of flow velocity on two parameters, coverage time and characteristic diameter, was analyzed and a classical power law was *developed* for the influence of the flow velocity on pitting rate for all three materials.

4. Investigation on coalesced effect of cavitation and silt erosion

The coalesced effect of sand and cavitation erosion can be observed in high velocity regions such as the needle of a Pelton turbine, guide vanes and runner blades of a Francis turbine. The *inlet region of a Francis turbine runner* has been found to be themost affected by the combined effect of cavitation and sand erosion, and this has been observed in the inlet region of runner blade where it joins with the hub and shroud as shown in Fig. 1. Cavitation erosion under such conditions is caused by collapse of bubbles generated at the guide vane shaft in the gaps between the vane and face plate. The cavitation damage in the Pelton bucket together with sand erosion is shown in Fig. 2. Fig. 3 shows the ripples formed by sand erosion in the needle. Figs. 4 and 5 *present the combined effect of sand erosion and cavitation with sharp pits and damage of a guide vane*, *respectively*. A groove formed due to a horse shoe vortex in the presence of sand *is illustrated* in Fig. 6.

The recommendation of IEC 60609 for the purchaser to enter into a mutually acceptable agreement with the proposed contractor for a combined cavitation and particle damage guarantee sounds simple in principle but is extremely difficult to apply in practice. Contractors are understandably unwilling to guarantee their products against particle erosion when the incoming particle conditions cannot be entirely controlled. A cavitation guarantee is meaningless if the hydraulic surfaces are aggressively attacked by

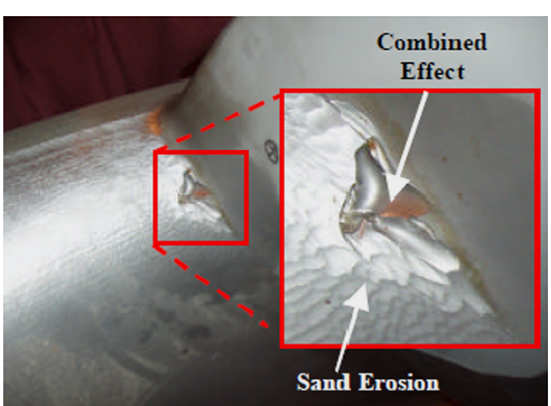

Fig. 1. Eroded part of Turbine Runner with pure sand erosion and combine effect demarcated [27].

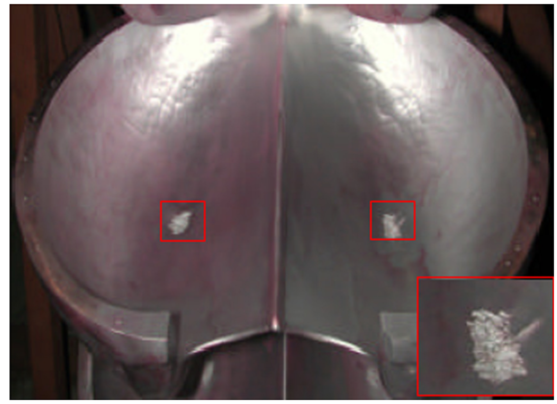

Fig. 2. Pelton bucket with cavitation induced erosion at the marked areas [27].

Fig. 3. Pure Sand Erosion indicated by wavy pattern in the needle [27].

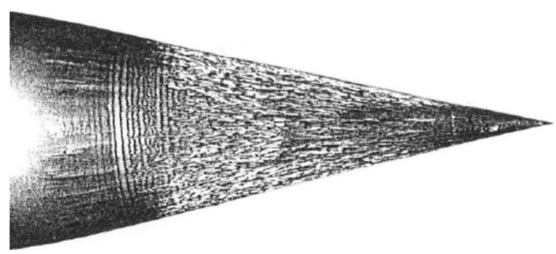

Fig. 4. Combined effect of cavitation and sand Erosion in the needle [27].

Fig. 5. Erosion in the guide vane [27].

Fig. 6. Horse shoe vortex erosion in the facing plate caused by the guide vane [27].

particles [19]. The *coalesced* effect of silt erosion and cavitation is more pronounced than their individual effects.

Rao et al. [20] presented long term cavitation and liquid impingement erosion. The modeling methods were proposed by different investigators, including the curve fitting approach and a power law relationship. The importance of the different models discussed using data from both cavitation and a liquid impingement device was investigated.

Jin Hengyun et al. [21] presented the role of sand particles on the rapid destruction of the cavitation zone of hydraulic turbines. They analyzed a worn surface of 18Cr–8Ni steel tested in a venturi device at a hydroelectric power station in the flood season. There are two types of damage: (i) smooth erosion in the area of regular fluid flow and (ii) in the regions where cavitation occurred, which *were studied*. The sandy water venture device is shown schematically in Fig. 7. The impingement attack of sand particles was so severe that it not only lead to metal deformation and damage but also fracture of the sand particles themselves. *The sand particles, cavities, cracks, cutting scars and fatigue patterns on the sponge-like worn surface were observed.*

Sato et al. [22] experimentally studied coupled damage caused by silt abrasion and cavitation erosion. The quantum of damage due to the coupled action of cavitation erosion and silt abrasion of artificial silt (Al_2O_3) was predicted. The magnitudes of the acoustic emission energy, impact pressure and material damage rate caused by the cavitating jet impingement were found to be more than those caused by the non-cavitating one. The submerged jet experimental apparatus that was used is as in Fig. 8. Fig. 9 shows

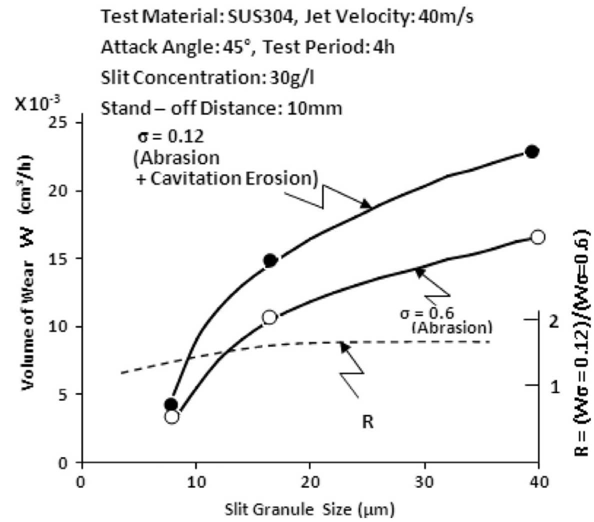

Fig. 9. Silt granule size and volume of Wear [22].

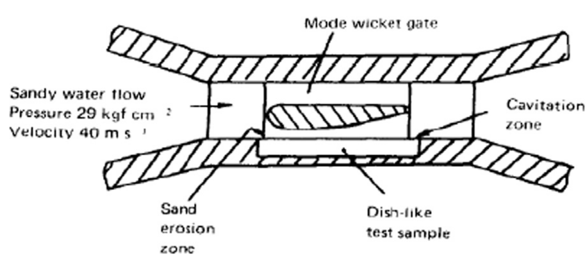

Fig. 7. The sandy water venture device for erosion–cavitation pitting [21].

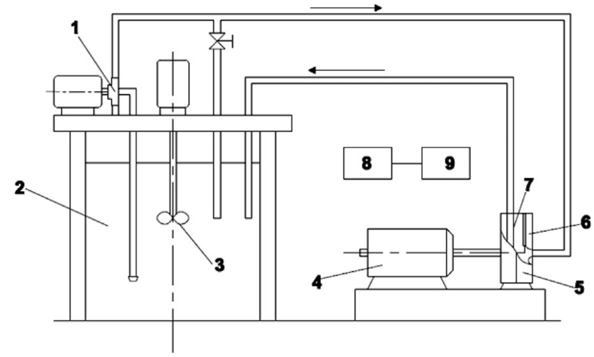

Fig. 10. (Left) Rotating Disk Equipment (1, pump; 2, cycling water; 3, stirrer; 4, motor; 5, work chamber; 6, stemming plate; 7, rotating disk; 8, speed measuring device; and 9, motor controller) [23].

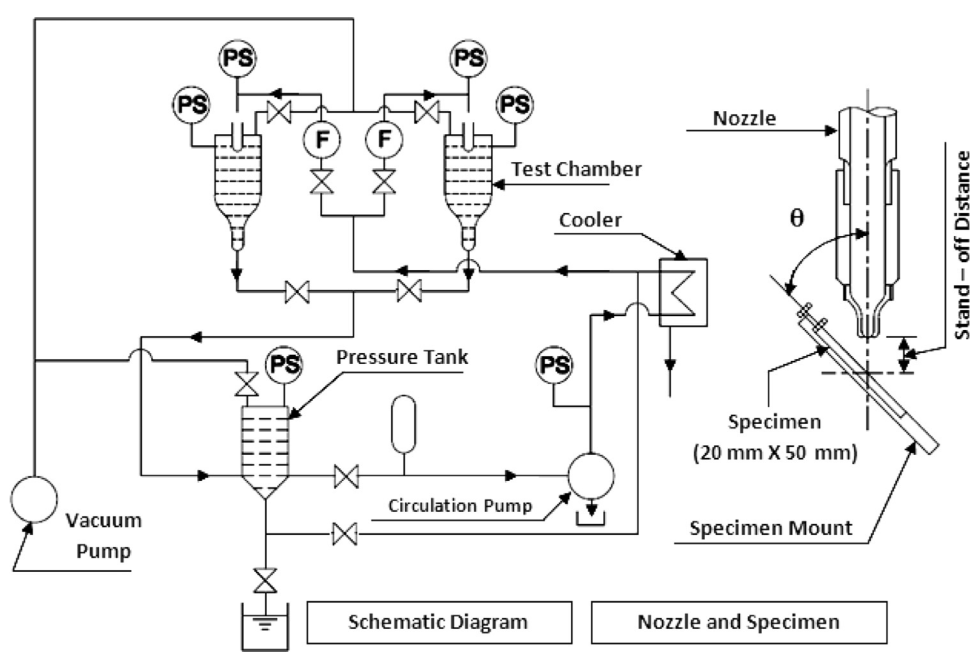

Fig. 8. Submerged jet experimental apparatus [22].

Table 1
Parameters of the rotating disk test [23].

Service condition	Sand content (kg m^{-3})	Temperature (°C)	Rotation speed (rev min^{-1})	Cavitation activating source
Cavitation erosion	0	20	2900	∅ 11.3 mm, deep blind hole
CAACE	16–17	20–30	2900	∅ 11.3 mm, deep blind hole
Abrasion	16–17	20–30	2900	None

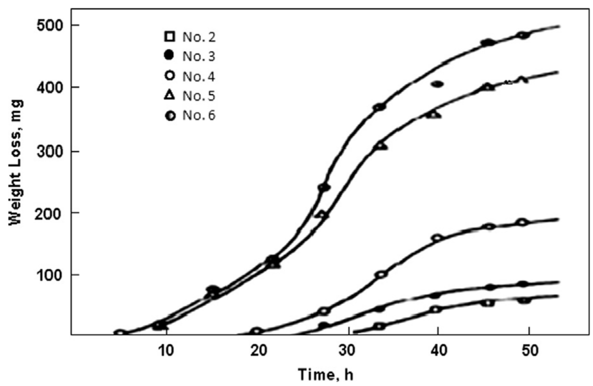

Fig. 11. (Right) Weight Loss curves of the cavitation [23].

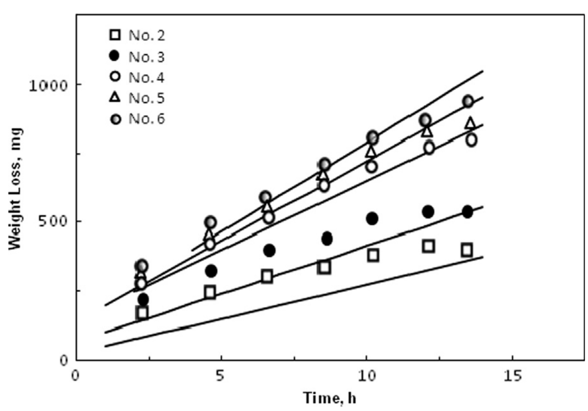

Fig. 12. Weight loss curves of abrasion [23].

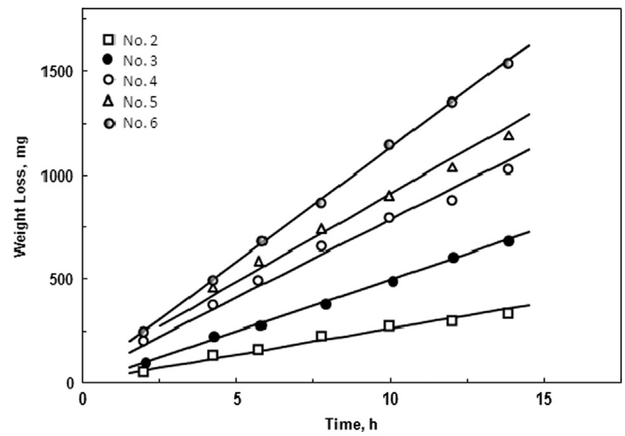

Fig. 13. Weight loss curves of CAACE [23].

the relationship between the silt granule size and erosion damage rate. The erosion damage rate *was* found to be increased with larger silt granule size under $\sigma=0.6$ and 0.12. However, it increased sharply with silt sizes of 8–39 μm and gradually with sizes of 17–39 μm.

Kang et al. [23] studied the mechanism of combined action of abrasion and cavitation erosion on some engineering steels. The abrasion and cavitation erosion properties as well as the relevant failure mechanisms of several steels to be used for hydraulic turbine parts were *investigated*. The experiment was performed on rotating disk equipment as shown in Fig. 10. The experiment was performed under three different test conditions as shown in Table 1. The weight loss curves of the cavitation erosion, abrasion and combined action of abrasion and cavitation erosion (CAACE) tests of the steels for different sample sizes mentioned are shown in Figs. 11, 12 and 13, respectively. It was also studied that the failure mechanism of steels used in sand carrying water is a weighted sum of the failures of abrasion and cavitation erosion. The weight loss rate W_{c+a} can be calculated as

$$W_{c+a}=a(1/(\varepsilon_f Hr)\hat{}2)+\beta(1/Hr) \quad (6)$$

where ε_f is the true fracture strain, *Hr is hardness in Rockwell scale*, and α and β are constants related to the weighted co-efficient of cavitation erosion and abrasion, respectively.

Mei and Wu [24] studied the cavitation erosion rate in sediment carrying flow that is the effects of silt concentration on the cavitation behavior and intensity of cavitation erosion. They presented the major results of field observation and analysis of extensive laboratory research. *Inception cavitation by measurement of the cavity length using NACA* 4412 *airfoil in a water tunnel was determined. The study found that* in clear water, the cavity length does not change for a given cavitation number but with silt laden flow, the status of cavitation number for a certain cavity length changes with variation of sand concentration.

Li [25] presented cavitation enhancement in silt erosion. *The intrinsic understanding of* cavitation enhancement using three examples was discussed: (i) correlation of material resistance with cavitation (bubble) characteristics at the micro-scale level, (ii) correlation of material resistance to silt erosion with the particle size and (iii) the influence of cavitation characteristics on the erosive power that the particle gained from the cavitation source. Also the nature of cavitation phenomenon at the micro-scale level from the viewpoint of the interaction between fluid-bubble and particle-material was reviewed.

Li [26] studied cavitation enhancement of silt erosion with an envisaged micro-model. By reviewing the phenomenon from the viewpoint of fluid particle interaction the postulated model was presented from the viewpoint of a driving force. This model suggested that the cavitation enhancement is achieved by capturing particles and holding them at the jet center, accelerating them to an extremely high velocity and turning their sharpest (cutting) edge towards the material.

Thapa et al. [27] studied the combined effect of sand erosion and cavitation in hydraulic turbines. *The experimental study was carried out* on a rotary disk apparatus (RDA). The RDA setup runs with (i) no sand in water to generate cavitation, (ii) without cavitation inducers to stimulate pure sand erosion and (iii) with

cavitation inducers and controlled amount of sand. *The individual and combined effects were observed in plain stainless steel and WC–CO–Cr ceramic coating applied by High Velocity oxygen fuel* (*HVOF*) *technique*. No particular pattern of erosion was found in the case of pure sand erosion; however, amount of erosion is apparently more than that in the case of pure cavitation. A clear removal of paint due to passage from both sides of the cavitation inducer towards the wake can be clearly noticed in Fig. 14.

Fig. 15 shows the progressive erosion pattern due to combined effect of sand erosion and cavitation in a non-coated region for a total test period of 4.5 h with sand of different sizes ranging from 90 to 212 μm. A progressive increase in depth of the horseshoe groove in the wake side of the cavitation inducer is evident. As the test proceeds the erosion groove propagates further and covers a larger area. *The study presented* that the combined effect of sand erosion and cavitation is more pronounced than their individual effects. There is no significant effect of cavitation alone on the HVOF coating but the combined effect of sand erosion and cavitation was visually observed.

Dunstan and Li [28] carried out a numerical study on cavitation enhancement of silt erosion. The silt particles gaining extra-damaging potential from the collapsing bubbles using the proposed micro-model by Li [26] was discussed. *A simplified model was employed which considered a single silt particle entrained in the micro-jet of a collapsing cavitation model*. CFD simulation was conducted using commercial code STAR CCM+ and a simplified analytical approach (written in MATLAB). Results were obtained from both methods and supported the mechanism of the micro-model that the silt particle damage potential to nearby solid boundary was largely enhanced through the acceleration of particle by the micro-jet of collapsing bubble in which the particle was entrained.

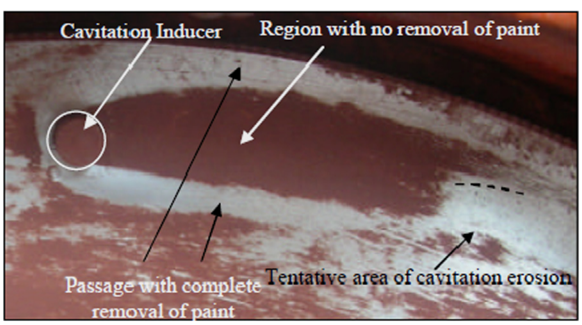

Fig. 14. Typical regions observed near cavitation inducer [27].

Weili et al. [29] *studied* numerical simulation of cavitation characteristics in two phases flow (pure water and solid–liquid) conditions in a Kaplan turbine. A particle trajectory model was used to investigate the region and degree of runner blade abrasion in different conditions. The concentration distribution of sand over the blade pressure side and suction side with different sand diameter of 0.005 mm, 0.024 mm and 0.1 mm under the condition of small discharge where the sand concentration was 1% was observed. The maximum cavity volume fraction increased gradually with diameter of sand under the same sand concentration at the inlet. When the diameter reaches 0.1 mm, the sand concentration distribution on the blade pressure side is obviously non-uniform, and the gradient is very big. Fig. 16 illustrates the cavity volume fraction distribution on the blade and general tendencies of cavity volume fraction and pressure distribution at the pressure side and suction side of blade. The efficiency change with sand concentration is shown in Fig. 17. *The study found that* the efficiency with two phases cavitation in clean water was 89.52%, which was 87.84% in sediment flow, decreasing by 1.68%.

Gregorc et al. [30] studied the impact of solid particles on the development of cavitation flow conditions around a hydrofoil. Different mixtures of silt particles and water were considered during experiments in a cavitation tunnel. The estimated measurement errors for pure water (Mt/Mt_0) and for three mass fractions, as evident, are given in Table 2.

The effect of the particle was observed using an addition phase particle dispersion model (Euler–Euler). Numerical modeling was performed using a commercial CFD program. The test was performed on a small cavitation tunnel at the faculty of Mechanical Engineering at the University of Maribor (FS) and is shown in Fig. 18. In the first phase, all measurements were performed without particles in order to compare the impact of the particles on the development of the vapor phase. The boundary between the influence of cavitation and the unaffected area of cavitation can be clearly observed in Fig. 19. Fig. 20 shows the results of the CFD simulation of the vapor phase formation on the surface of the “initiator” block during the parametric analysis of the solid shear

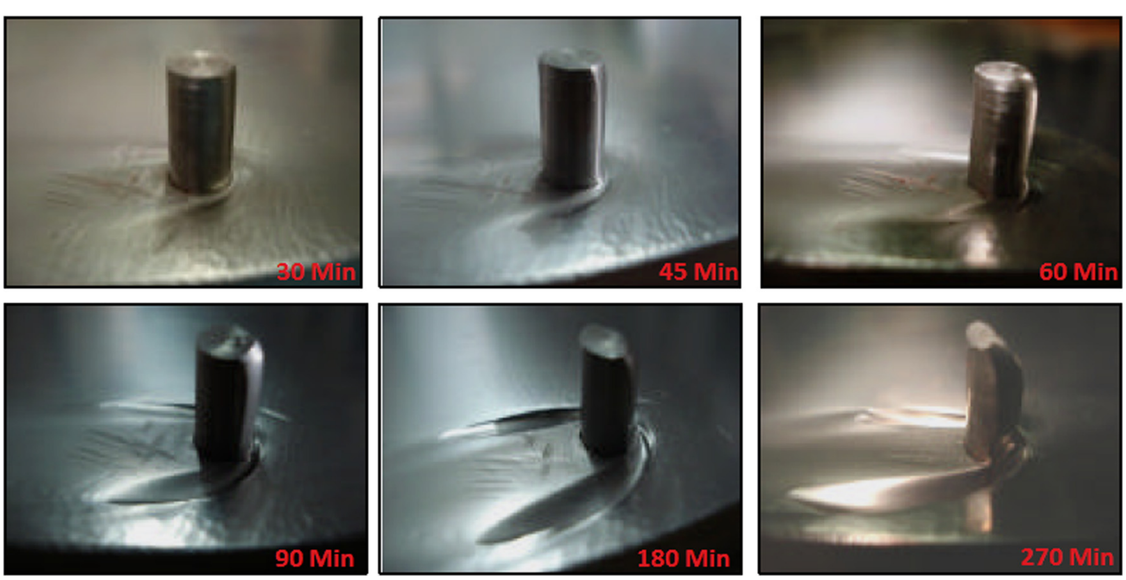

Fig. 15. Progressive erosion pattern caused by combined sand erosion and cavitation in non-coated region of test disk with total test duration of 4.5 h [27].

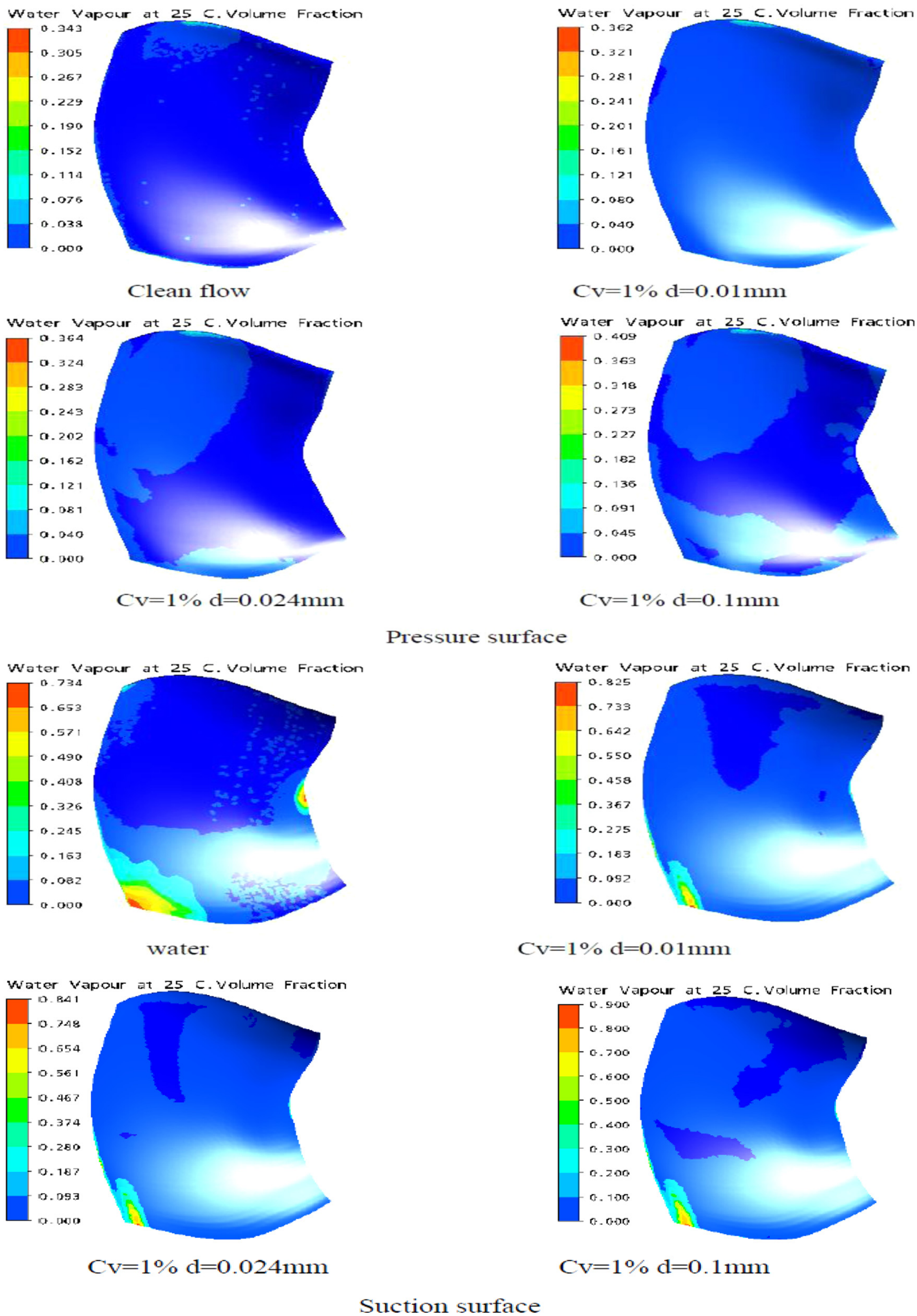

Fig. 16. Cavity volume fraction distribution at the blade [29].

viscosity. The increase of the vapor phase in the case of dispersed phase mass fraction is 0.0032 and shear velocity is 0.876 compared with pure water. Fig. 21 shows that the particles increase the fraction of vapor volume on the hydrofoil profiles, depending on the volume fractions of the added particles. The present approach can be used to predict the cavitation in hydraulic machinery in cases of the presence of solid particles.

Gregoc et al. [31] carried out an experimental analysis of the impact of particles on the cavitating flow. In a cavitation tunnel, the effect of particles in the water on the change of the relative

ratio of torque and the relative intensity of cavitation-noise on a hydrofoil for three different mass fractions of particles was analyzed. The impact of particles on lift–drag forces and noise was analyzed and results were compared with the measured relative values of clean water free of particles. It was clearly shown that the number of particles increases the intensity and extent of cavitation. A comparison of results obtained under different situations was made and is shown in Fig. 22. The value of maximum amplitude of noise is reached in frequency in the range of 1 kHz. Number of particles markedly increases the intensity of sound at a frequency of 315 Hz and between 4 and 12 kHz.

Jian-hua and Wen-juan [32] experimentally investigated the effect of sand particles on cavitation damage, mainly focusing on the particle size and the concentration. The experiment was carried out on the samples for cavitation damage, which were made of AMST 1045 carbon steel using special vibratory apparatus. It was found that the increase of the sand size or concentration would aggravate the cavitation damage if the sizes are larger than the critical sizes. *Three concentrations of sand were tested*, 25 kg/m^3, 50 kg/m^3, *and* 85 kg/m^3, *for five sizes of sand*, d_{50}=0.531 mm, 0.253 mm, 0.063 mm, 0.042 mm, and 0.026 mm, *with* 0 mm *meaning that the results are for distilled water without sand particles. The duration of the test is* 4 h. Fig. 23 *shows the results of the effects of the sand particle size and concentration on the cavitation damage, in which WL is the weight losses of the samples and C is the particle concentration in the liquid.*

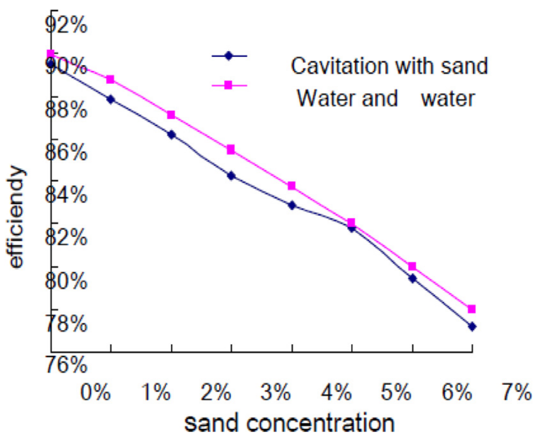

Fig. 17. The efficiency change with sand concentration [29].

Table 2
Particle mass fraction used in the experiment and measurement errors – Mt/Mt$_0$ [30].

Mass fraction	ζ [–]	Estimated measurement errors – STDEV (Δp=0 bar)
Pure water	0	2.1
Fraction 1	0.001	2.9
Fraction 2	0.0016	3.1
Fraction 3	0.0032	3.6

5. Conclusion

An extensive literature review on cavitation and erosion due to silt in turbines has been carried out and the followings conclusions are drawn:

(i) *Many investigators studied the processes of silt erosion* and *cavitation, and the coalesced effect of both in hydro turbines through experimental and analytical investigations.*
(ii) *Some of the investigators studied the effect of silt parameters such as silt concentration, particles size, velocity and operating parameters* (*angle of attack and time*) *on erosion in hydro turbines. Based on their results they have attempted to develop*

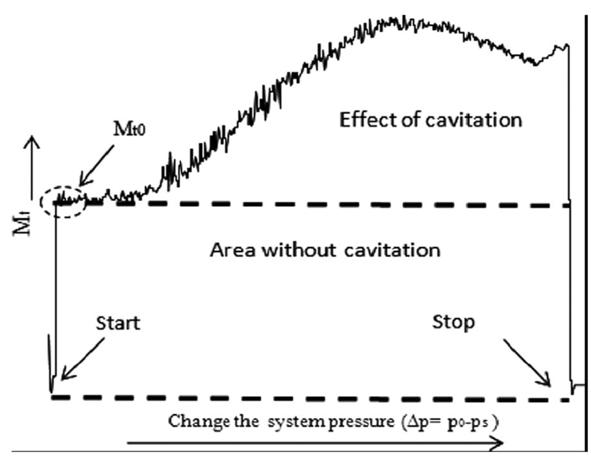

Fig. 19. A case measurement Mt of the profiled testing hydrofoil [30].

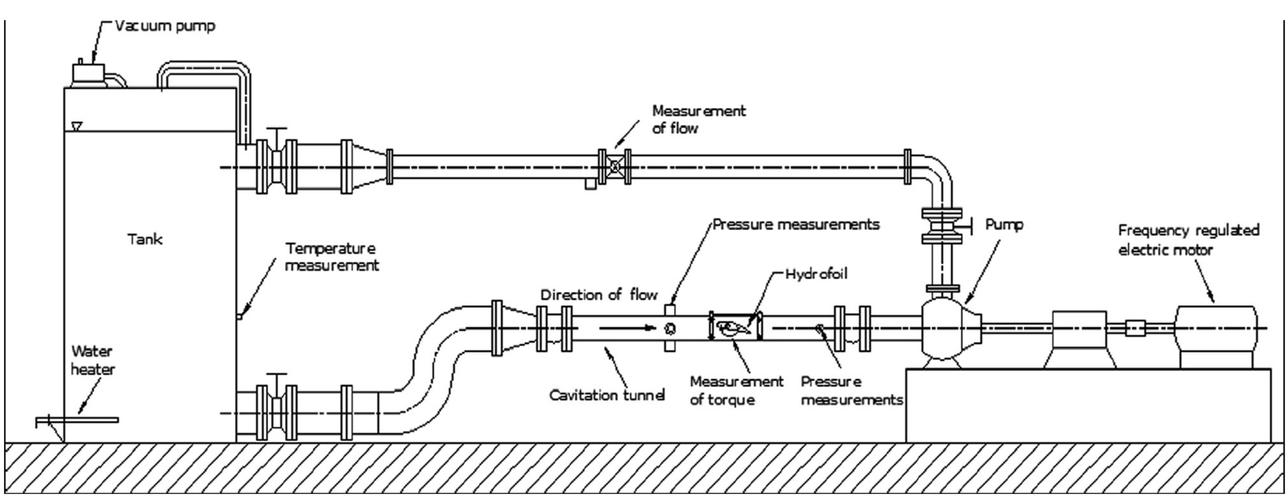

Fig. 18. Schematic of cavitation tunnel [30].

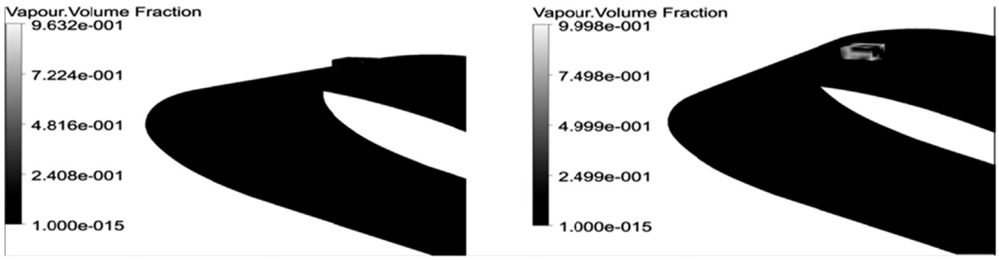

Fig. 20. Comparison of vapor volume fraction simulation without particles (left) and with particles (right), mass fraction = 50.0032 at equal pressure difference = 0.02 bars, and discharge = 15 kg/s [30].

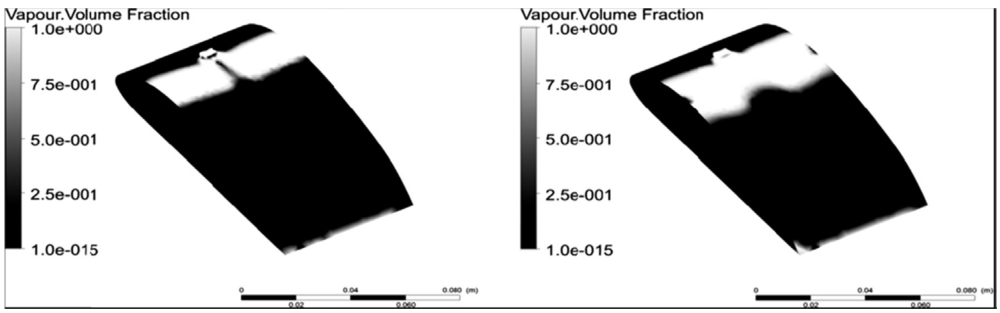

Fig. 21. Comparison of vapor volume fraction simulation without particles (left) and with particles (right), mass fraction = 50.0032 and shear viscosity = 50.87 at equal pressure difference = 0.35 bars [30].

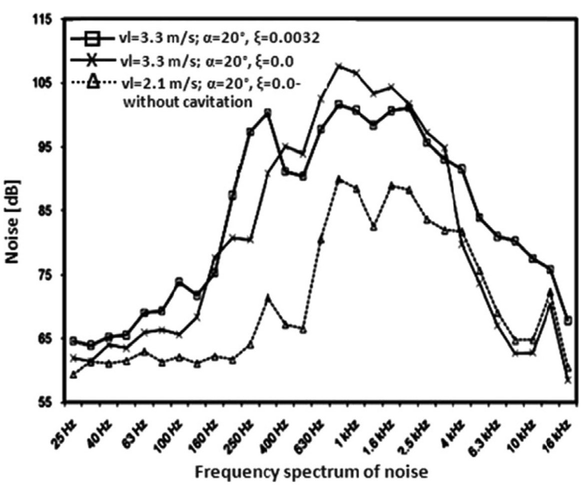

Fig. 22. The impact of particles on the frequency range of cavitation noise [31].

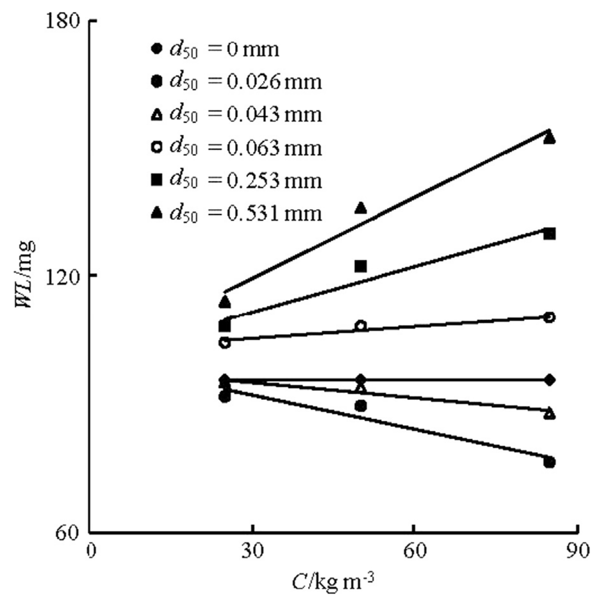

Fig. 23. Variation of WL with C and d_{50} [32].

correlations for efficiency and wear rate as a function of silt parameters.

(iii) *In the case of cavitation, investigators have predicted the cavitation intensity, rate of erosion progress, nature of the cavitation phenomenon and erosion rate on different materials of turbine components.*

(iv) *A few studies are available on the coalesced effect of silt and cavitation in hydro turbines in order to predict the weight loss rate of turbine components. These studies were basically carried out to suggest the repair and maintenance of turbine components through coatings. However, more investigations are required for further improvements.*

Extensive studies are required to develop a fundamental understanding of the coalesced process and to predict the impact of coalesced effect of silt and cavitation under different operating parameters.

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